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SOME WIND TUNNEL DESIGN PROBLEMS

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SOME WIND TUNNEL DESIGN PROBLEMS

W. K. Cook,[1] M. ASCE

The paper concerns the design of the wind tunnels and associated test facilities of the Arnold Engineering Development Center at Tullahoma, Tennessee. Some of the Civil Engineers problems in the selection of materials, the provision of unusual structures to meet exacting aerodynamic requirements, and the provision for wide temperature variations are discussed.

This paper will discuss some of the problems encountered in the design of test facilities for the Arnold Engineering Development Center. It is concerned primarily with the problems encountered in the design of wind tunnels which in general do not fall within the day to day experiences of most Civil Engineers. The best combined efforts of engineers of many branches of the profession are required to accomplish the design. All, however, find their work governed by and subordinated to the requirements of the Aeronautical Engineer. Since the test facilities are being built for the purpose of obtaining performance data by flight simulation, it is reasonable to expect the requirements of the Aeronautical Engineer to be paramount. The Civil Engineer often finds himself forced to extreme limit of his ability and ingenuity in designing structures to meet the requirements imposed upon him.

Testing facilities such as these are unique in many ways. In order to avoid early obsolescence, it is necessary to try to predict the future performance of aircraft and missiles and their propulsion systems and to incorporate into present designs either the means for doing the development and evaluation testing which will be required or provisions so that necessary alterations or extensions can be made.

The basic design data in many instances were either meager or non-existent. This was true primarily in the Aeronautical field but was also a factor in the Civil Engineering field. Before many design decisions could be made with any reasonable degree of confidence, many aerodynamic, structures and materials research programs had to be established, then executed on a schedule coordinated with the facility design schedule.

Before proceeding further, some description of what a wind tunnel is appears to be in order. It is a tube or passage thru which a stream of air is flowing and which is utilized for the purpose of simulating flight under laboratory controlled conditions. Wind tunnels may be very small or very large, simple or complex. Those at the AEDC are either large or complex or both. In some, such as in the test sections of the Engine Test Facility, the flow of air is once thru, from atmosphere, thru the test section, to atmosphere. The wind tunnels of the Gas Dynamics Facility and the Propulsion Wind Tunnel Facility are of the recirculating type. The latter type is preferred where

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applicable as it is more efficient in the use of power. The flow of air is obtained by the use of compressors. In the Propulsion Wind Tunnels, the axial flow compressors can be visualized as giant fans installed in series to give the required stages of compression. In the Engine Test Facility and the Gas Dynamics Facility the compressors are either of the centrifugal or axial flow type similar to those used in blast furnaces. The compression ratio required to move the air thru the wind tunnel at low subsonic speeds is very small but increases rapidly for the supersonic speeds. As an example, the compression ratio available for the operation of one of the supersonic tunnels of the Gas Dynamics Facility is 1200:1. In this process the weight of air contained in 1200 cu. ft. of volume before compression is squeezed into 1 cu. ft. of volume.

All of the various compressors, coolers, heaters, driers and other pieces of apparatus which collectively make up a wind tunnel facility have but one purpose; to supply the test section with air at the proper pressure, temperature and state of dryness for the required testing. As the name implies the test section denotes that portion of a wind tunnel where the actual testing is accomplished. It is here that the models to be tested are mounted in the airstream and subjected to simulated flight conditions. Models are equipped with up to hundreds of instruments to measure and record forces, moments, pressures and temperatures. Numerical values of these parameters can be automatically processed in electronic computing machines to the end that significant test results are almost immediately available to the test engineer.

In order to more clearly understand the phenomena that take place in the test section of a wind tunnel, especially under conditions of supersonic flow, the definition of a very few terms basic to test facility design and operation appears to be in order.

1st, Mach No. This is the ratio of air speed to the speed of sound. Mach one being the speed of sound, Mach two, twice the speed of sound and so on. It is interesting to note that the speed of sound varies as a function of the absolute temperature. At 59^{o}F the speed of sound is 1,116 ft. per second or 762 miles per hour.

Second, the terms Stagnation Pressure and Stagnation Temperature. These are terms to denote the pressure and temperature in the stilling section ahead of the test section. In this region, the flow area is large and the velocity low.

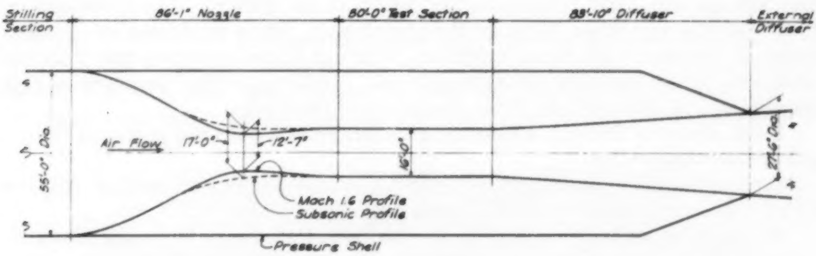
Third, Reynolds Number. This is a dimensionless number involving the parameters of density, velocity, length and viscosity.

It is an established principle of fluid dynamics that if the Reynolds number is maintained constant, the flow around bodies of similar shape will be similar regardless of the relative size. By providing sufficiently high pressure and consequent high density it is possible to simulate large bodies with relatively small models. This method of testing is particularly useful for aerodynamic testing where the required results can be obtained from small models. In the Gas Dynamics Facility, stagnation pressures as high as 2,500 lbs per square inch are employed. However, it is not feasible to build small scale models of engines and facilities must be provided to test the full size engine.

Fourth, Transonic, Supersonic and Hypersonic. These are expressions with rather arbitrary selected limits. In general, transonic denotes speeds roughly from Mach 0.8 to 1.6. Supersonic, speeds from Mach 1.6 to 5.0 and hypersonic, speeds above Mach 5.0.

Slide 1, which shows the profile of the test section region of the Transonic

Propulsion Wind Tunnel, will serve as a basis for discussion of some of the phenomena occurring in the test section region, particularly in regard to the differences between subsonic and supersonic air flow. In a subsonic wind tunnel, the test section provides the smallest cross sectional area for air flow in the entire circuit. The subsonic profile is illustrated by the two outer lines which in this case represent the side walls of the nozzle. These walls are movable. The top and bottom walls are parallel and stationary. Changes in air velocity thru the test section are accomplished by changing the compression ratio. In some wind tunnels this is accomplished by changing the speed of rotation of the compressor. In the Propulsion Wind Tunnel, it is accomplished by changing the angle of the compressor stator blades.



PLAN

TEST SECTION REGION

TRANSONIC PROPULSION WIND TUNNEL

Figure 1

Once the speed of sound is exceeded, it is no longer possible to change the speed of the air by changes in compression ratio alone. Now, unfortunately, we must also change the geometry of the nozzle upstream of the test section, as it is necessary to expand the air downstream of the throat. The inner lines denote the highest speed or Mach 1.6 profile of the transonic nozzle. The positions for other Mach numbers lie intermediate to the extremes shown. At the throat the air velocity is equal to the speed of sound and the pressure has fallen to slightly more than half the stagnation pressure. The velocity at the test section is dependent entirely upon the ratio of the area of the throat to the area of the test section. Thus, a change in test section velocity requires a change in this area ratio, which necessitates a change in the position of the throat and the geometry of the entire air stream boundary to the test section. This becomes a rather formidable undertaking as it is necessary, in order to obtain the proper uniformity of the air flow, to maintain the required profile within a few thousandths of an inch. In some of the smaller wind tunnels, separate sets of rigid nozzle blocks are provided, one set for each Mach number at which tests are to be run. A change in Mach number requires that one set of nozzle blocks be removed and another set inserted. While this is a satisfactory method of securing speed changes in a small wind tunnel, it is obviously impracticable for the tunnels of the AEDC facilities. One only needs to imagine the delay and expense involved if this method were applied to the huge Propulsion Wind Tunnel. In the AEDC wind tunnels, the profile is formed by flexible steel plates positioned by numerous jacks. These jacks must of course, be accurately

controlled in order to obtain the required profile and also to avoid over-stressing the plate during Mach number changes.

Expansion to produce supersonic velocity in the test section decreases the pressure and the static temperature. As an example, at Mach No. 3 with a stagnation pressure of one atmosphere gage, which amounts to 2,120 lbs. per sq. ft., and a stagnation temperature of 650°F, the test section velocity will be 2,900 ft. per second, or 2,000 miles per hour, the test section static temperature will be -67°F and the pressure will be 58 lbs. per sq. ft. absolute.

We can now give some thought to the role of the Civil Engineer in the design of wind tunnels. As the AEDC facility design was handled in our office, Civil Engineers were assigned the responsibility of accomplishing the design of the conventional structures such as buildings, craneways, foundations, etc., and in addition the design of the ducting, test chambers, cooler shells and other items of the air circuit. Many problems of course, arose in the design of these facilities. The out of the ordinary run of design problems which confront the engineer can, I believe for the purposes of this discussion, be divided into three broad classifications.

First, those of finding, selecting and obtaining a suitable material for a particular application.

Second, those of providing some of the shapes and other physical features which the Aeronautical Engineer requires.

Third, the problems brought up by the extreme ranges of temperature thru which these facilities operate. Problems in this category divide themselves into two sub-classes. One the problem of providing means of articulation so that excessive stresses will not be developed by movements induced by temperature differentials, the other the problem of eliminating, reducing or minimizing the temperature differentials and consequent stresses when articulation is impossible or impracticable.

Some of the particular materials problems will be mentioned later. There are of course, many others. Steels are required which will be suitable for temperatures down to minus 120°F and up to 1200° or 1500°F. Some material with the ductility of steel which could withstand the direct impingement of jet flames at 3000°F or higher would be very nice to have. It is difficult to find paints suitable for high temperatures especially those suitable for field application where thermal curing is most often impracticable. Sealing of the sliding surfaces of the wind tunnel nozzles and similar parts which must be nearly air tight and which operate at temperatures up to 650°F has been a particularly difficult problem. This has been a problem of physical shape as well as material and is now solved except for the extreme top of the temperature range. The silicones, which can be made with characteristics similar to rubber have proved suitable for these high temperature applications. This is a relatively new material which has been greatly improved in the last few years. The wind tunnel designer often finds himself longing for materials which do not exist, such as strong materials with a modulus of elasticity many times that of steel or at other times a mere fraction of that of steel. A good many problems of design would disappear if we had a suitable material with zero co-efficient of expansion over a wide range.

Slide 2 illustrates the low Mach test section of the Gas Dynamics Facility. The test section is 40 inches square. The speed range is from subsonic to Mach 5.5. It is a good example of problems of the second type. The flow of air is from left to right. Air initially goes through a screen section where uniformity of flow is achieved. Then through the throat and through the test

section where the model under test is mounted. Downstream from the test section we have a converging, diverging diffuser for pressure recovery, then a cooler and then downstream ducting to lead the air to the compressor to start the circuit all over again. The throat is adjustable in the manner previously described. However, in this case the speed range is much greater and relative changes in shape are therefore much more pronounced. There are a total of 39 jack stations. Each jack station consists of two jacks above and two below. These jacks are powered by electric motors driving through magnetic clutches. The air stream boundary is a stainless steel flexible plate 0.43 inches thick and 40 inches wide. The type of steel used is stainless W produced by the U.S. Steel Corporation, heat treated to give a limit of proportionality of 100,000 to 110,000 lbs. per sq. in. Ultimate strength is approximately 170,000 lbs. per sq. in. Design working stresses are about 75,000 lbs. per sq. in. Jack stations are at approximately 6-1/2" centers in the throat. Attachment lugs are machined out of the solid plate to avoid welding or other means of attachment. Incidentally, stainless W is a rather sensitive material when heat treated to these high physical properties and considerable research and testing was required to establish the reliability of these properties.

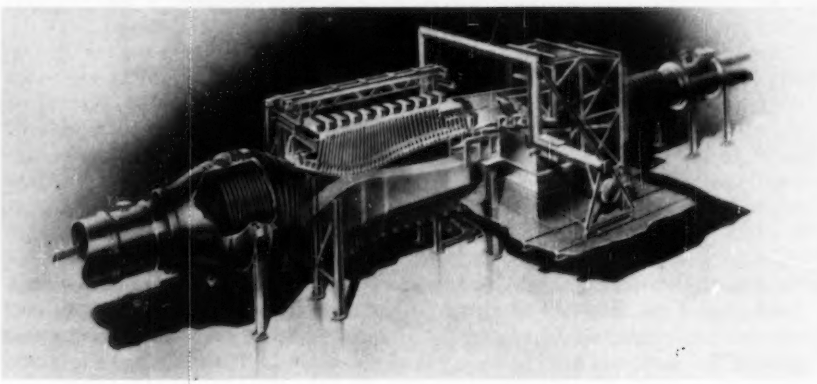


Figure 2
Supersonic Test Section
Gas Dynamics Facility

The converging, diverging diffuser is also adjustable in order to secure maximum pressure recovery. It is adjustable in long straight chords rather than in continous curvature as used for the nozzle.

The matching of the curved plate to the desired aeronautical profiles of the nozzle thru out the rather large speed range proved to be a very difficult problem. The problems of the Aeronautical, Control and Civil Engineers can well be appreciated when it is realized that predetermined positions must be maintained and be repeatable within about five thousandths of an inch. As a comparison, the thickness of a sheet of writing paper is about three thousandths of an inch.

Slide 3 illustrates the high Mach test section of the Gas Dynamics Facility. Its speed range is entirely above Mach 4.5. It also has a 40 inch square test section, an adjustable nozzle and an adjustable converging, diverging diffuser. The stagnation pressure is 2300 lbs. per sq. in. The high stagnation

temperature makes it mandatory that all walls including moveable walls be water cooled in order to protect the metal and to avoid excessive distortions. This tunnel provided problems similar to most of those in the low Mach tunnel and added a good many more due to the very high stagnation temperatures and pressures. The top and bottom walls of the nozzle are symmetrical and moveable. Each wall is made up of a rigid rotatable throat block to vary the air passage, a short section of thin uniform thickness plate at the section of sharpest change in curvature and a following length of plate of varying moment of inertia. Stainless W is used thruout except for the throat blocks which will be discussed later. This arrangment, which gives a profile which satisfactorily matches the aerodynamic profile, was the result of many cut and try operations.

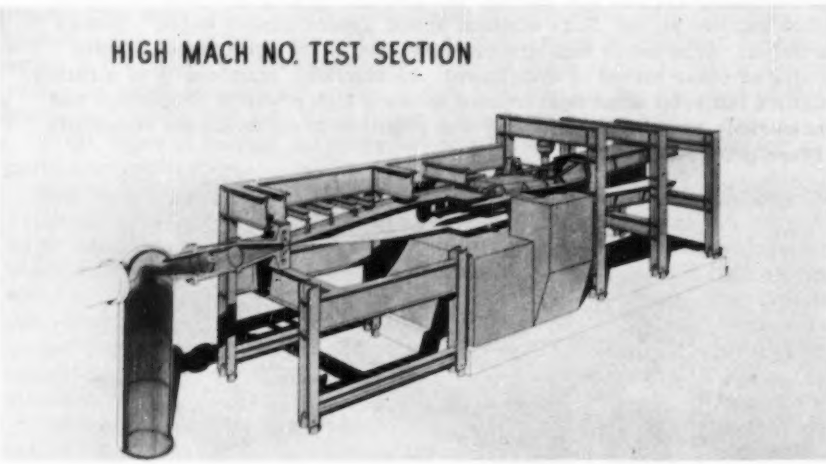


Figure 3
Hypersonic Test Section
Gas Dynamics Facility

Two design features are especially worthy of discussion. One is the throat and the other the thin plate immediately downstream of the throat. Heat transfer calculations determined that the throat material must be thin and have a high heat transfer rate in order to remove the heat from the air surface and deliver it to the water behind the plate. The material also must be strong to resist both the high loads from the air pressure and from the cooling water pressure. The material which most nearly meets these requirements is tungsten. A design was prepared consisting of a back up material, in which the water channels will be machined parallel to the air stream surface, to which the tungsten sheet, which had been match machined will be brazed. Since construction of this nature had never been previously tried, Battell Memorial Institute was engaged to perform the necessary experiments. The brazing must be accomplished at high temperatures in a controlled atmosphere. The readily available stainless W would have made an ideal back up material except that its coefficient of expansion is very different from that of tungsten. Molybdenum was determined to be the material most suitable, with a coefficient of expansion very nearly the same as tungsten, so that there could be reasonable expectation that the brazed surfaces

would not separate due to unequal contraction upon cooling. After several experiments with various brazing materials and methods, a satisfactory procedure for brazing was developed.

Now if we could find some source of a large enough tungsten sheet, a large enough molybdenum block and some industry with a large enough brazing furnace it would be possible to construct the throat. It is altogether probable that at first, alternate available materials will have to be used with some penalty in performance of the facility. This construction is, however, feasible for one of the smaller intermittent wind tunnels.

At the downstream end of the throat block there is a 16 inch length where a plate 0.30 inches thick is used. This plate contains closely spaced channels 0.16 in. in diameter for the cooling water. Drilling holes of 16 inch length in a plate this thin presents quite a problem. It has been determined that the work, which requires an expert craftsman, can be accomplished but in a very limited number of shops.

The fact that all engineering materials change length with change in temperature causes the wind tunnel designer a great deal of trouble and more often than not proves to be a major consideration in the whole facility layout. Slide 4 shows a good example of this. Nearly all the ducts or pipes operate thru a temperature range from ambient to several hundred degrees F. The inside air temperatures may be changed very rapidly if operation of the facility requires it. The articulation necessary to prevent excessive stresses in equipment or ducts has been accomplished in three ways. One, by flexure in the pipe itself by providing sufficient length in loops and bends. This method was used for the small high pressure piping but is only applicable for small pipe. Two, by providing expansion joints, and three, by providing rotation joints. In our wind tunnel work we have chosen to define an expansion joint in a pipe or duct as a joint which does not provide a means in the duct itself for transmitting the longitudinal forces across the joint. It does allow longitudinal movement of the duct on one side of the joint with reference to the duct on the other side of the joint. We have defined a rotation joint as one which allows an angle change at the joint, no longitudinal movement of the duct on one side with reference to the other, and one which transfers the longitudinal stresses in the duct across the joint. It is often very difficult and expensive to provide anchors to resist the large thrusts produced by the use of expansion joints. For this reason the designer endeavors to use rotation joints wherever possible. Some conception of the forces at joints can be had by considering that a pressure of one atmosphere or 15 lbs. per square inch is roughly equivalent to a ton per sq. ft. At one of the facilities it was necessary to provide an expansion joint in a 9 ft. diameter duct carrying 150 lbs. per sq. in. pressure. The resultant thrust force amounts to 1,500,000 lbs. which at one anchor is applied horizontally twenty eight feet above the base of the supporting foundation.

Slide 5 is a view of the Propulsion Wind Tunnel Facility. It is by far the largest facility at the AEDC. The facility consists of two separate wind tunnels with a common motor drive system. The smaller of the two is the Transonic Tunnel which covers the Mach range from subsonic to 1.6. It is a closed rectangular loop with centerline dimensions of 180 ft. by 383 ft. The compressor is 30 ft. in diameter and shell diameters vary from this figure to 55 ft. at the cooler and test section. The larger circuit is the Supersonic Tunnel which covers the Mach range from 1.4 to 4.5. The compressor is also 30 ft. in diameter and shell diameters are comparable to those of the Transonic Tunnel.

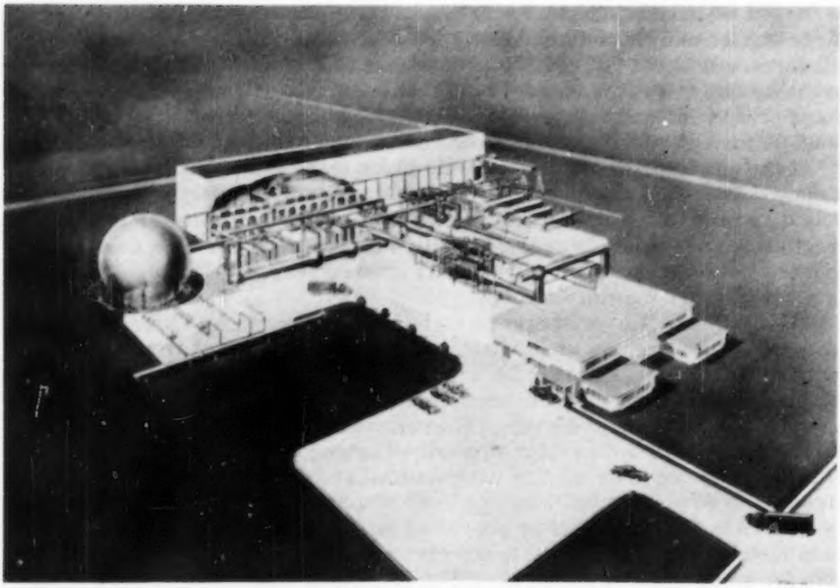


Figure 4
Gas Dynamics Facility

Figure 5
Propulsion Wind Tunnels

This facility together with the facilities which must operate to support it produces a demand for water of 150,000 gallons per minute and a power demand of 318,000 KW which is the upper load limit at present allowed on the Tennessee Valley Authority system which supplies the power. The hours of use of power of this order of magnitude are limited to the period between 10 P.M. and 5 A.M.

The total length of shaft for the assembly of the two compressors and their drive motors is approximately 500 feet. When completed, the compres sor system will be the largest rotating machine ever built. Shaft couplings are arranged to allow application of full power to either wind tunnel or half power to both wind tunnels simultaneously.

The driving units consist of two 25,000 HP wound rotor induction motors and two 83,000 HP synchronous motors which run at 600 revolutions per minute. The total driving power is then 216,000 HP. In order to start either of the tunnels it is necessary to evacuate the tunnels to about 50 lbs. per sq. ft. absolute pressure, bring the compressors up to speed with the wound rotor motors, and then when the synchronous motors are on the line, increase the pressure to that desired for the test. The increase or decrease rate of change of the electrical load is limited by the Tennessee Valley Authority to 30,000 kw per minute. The total operation of starting the tunnel is estimated to take about 15 minutes. The Engine Test Facility runs in support of the Propulsion Wind Tunnels to evacuate them in starting and stopping, to pressurize them in operation to remove the products of combustion during engine tests and to supply the dried air necessary to replace that used in combustion.

Slide 6 is an artist's conception of the Supersonic Compressor. It consists of eighteen stages in four barrels in order to cover the compression ratio range required for the Mach number range at the test section. By an arrangement of iris valves, it is possible to use one barrel alone or to use 1 to 4 barrels in series. The higher Mach numbers of course, require the use of all barrels. Flow is by-passed around the barrels not being used. To cut out a barrel it is necessary to uncouple it from the circuit and shift the iris valves. This can be done by remote control with the compressor stopped. The view shows the iris valves in position for use of the first and second barrels. The last two barrels are uncoupled and the air flow by-passes them. The transonic compressor is much smaller having but one barrel which is very similar to the first barrel of the supersonic compressor.

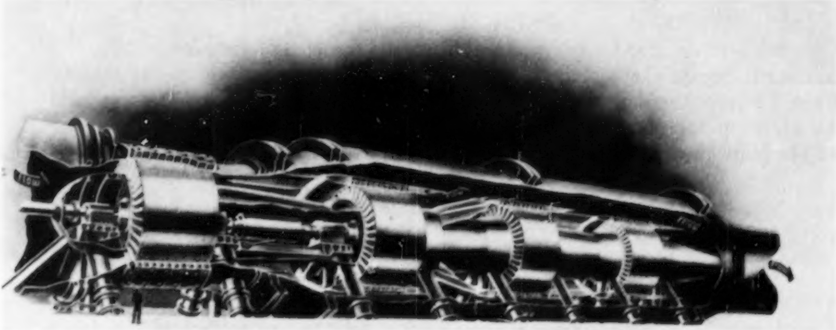


Figure 6
Supersonic Propulsion Wind Tunnel Compressor

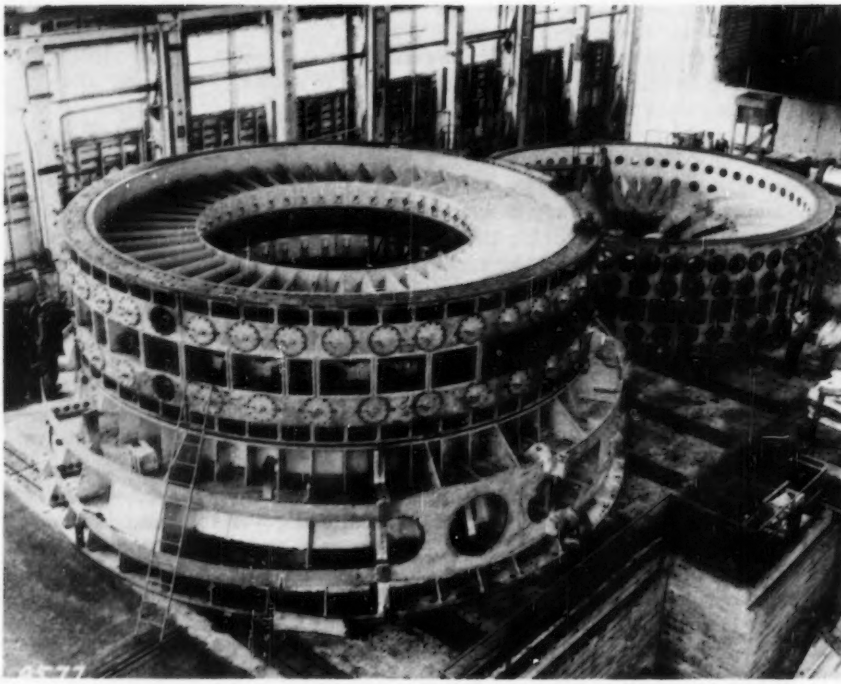


Figure 7
Stator Rings
Transonic Propulsion Wind Tunnel Compressor

A few slides made from pictures taken during manufacture of the transonic compressor will give some idea of the magnitude of the machine. Slide 7 shows the stator rings being assembled in the shop. The angle of the stator blades is adjustable by remote control. One stage of the rotor will occupy the space between two rings of stator blades.

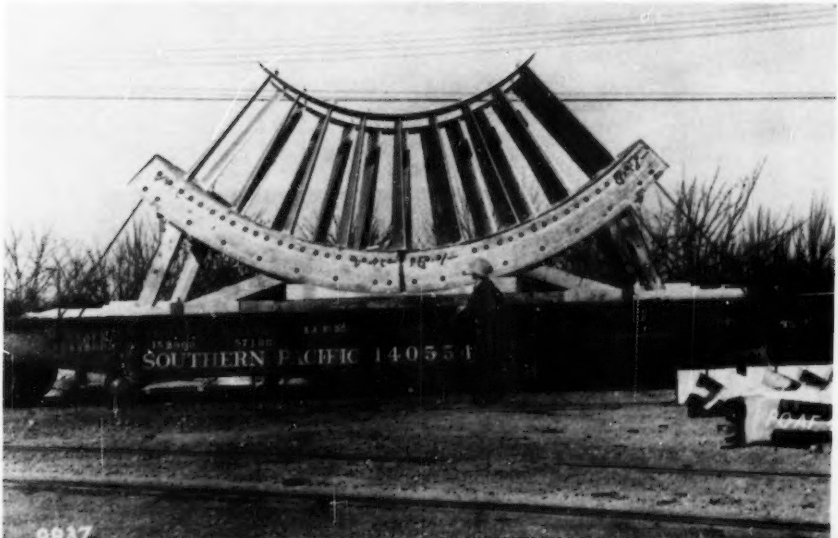


Figure 8
Stator Sector
Transonic Propulsion Wind Tunnel Compressor

This view (Slide 8) shows a sector of the stator ring being prepared for shipment to Tullahoma. A waterproof housing is yet to be constructed.

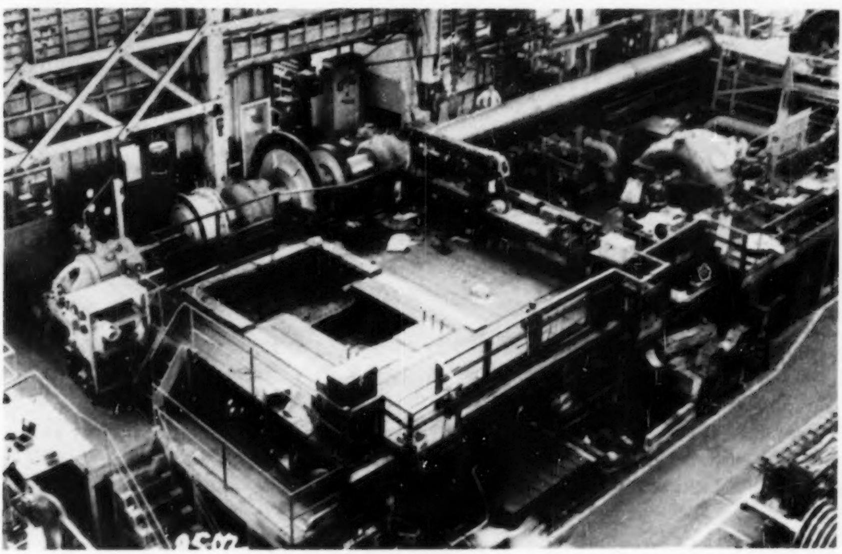


Figure 9
Drive Shaft
Transonic Propulsion Wind Tunnel Compressor

This is a view (Slide 9) of the transonic compressor drive shaft being dynamically balanced in the shop.

Figure 10
Rotor Blade
Transonic Propulsion Wind Tunnel Compressor

This (Slide 10) is a picture of the first completely machined blade for the transonic compressor. Each blade is 6 ft. high and weighs 1200 lbs. During operation the centrifugal force tending to pull the blade from the rotor disc amounts to 800 tons.

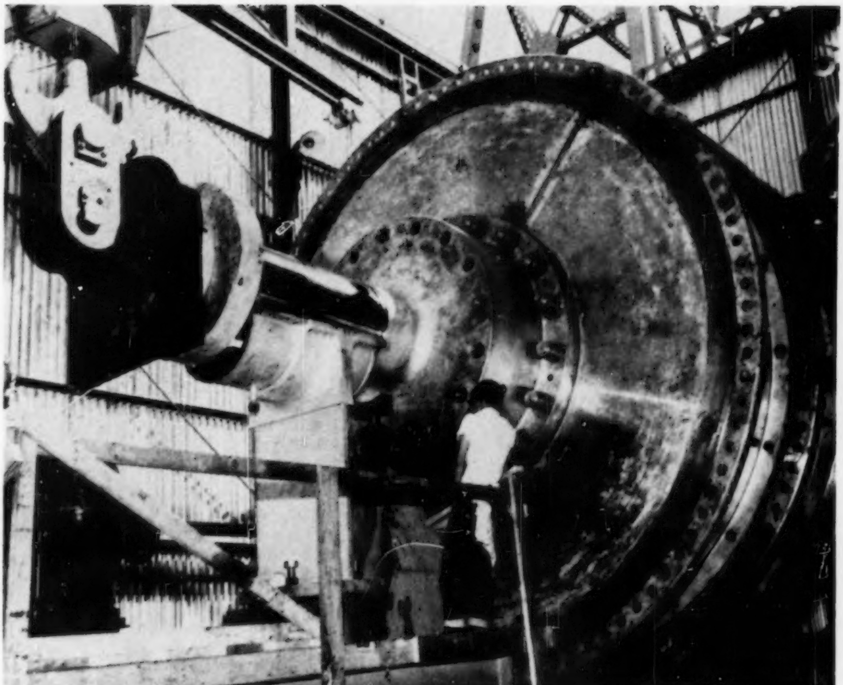


Figure 11
Rotor Discs
Transonic Propulsion Wind Tunnel Compressor

Slide 11 shows the start of assembly of the transonic compressor rotor at the site in Tullahoma. The view shows the rotor disc assembly which is 18 ft. in diameter. Blades such as those of the preceding picture will be attached to the rim and the assembly will then be set in its position in the wind tunnel.

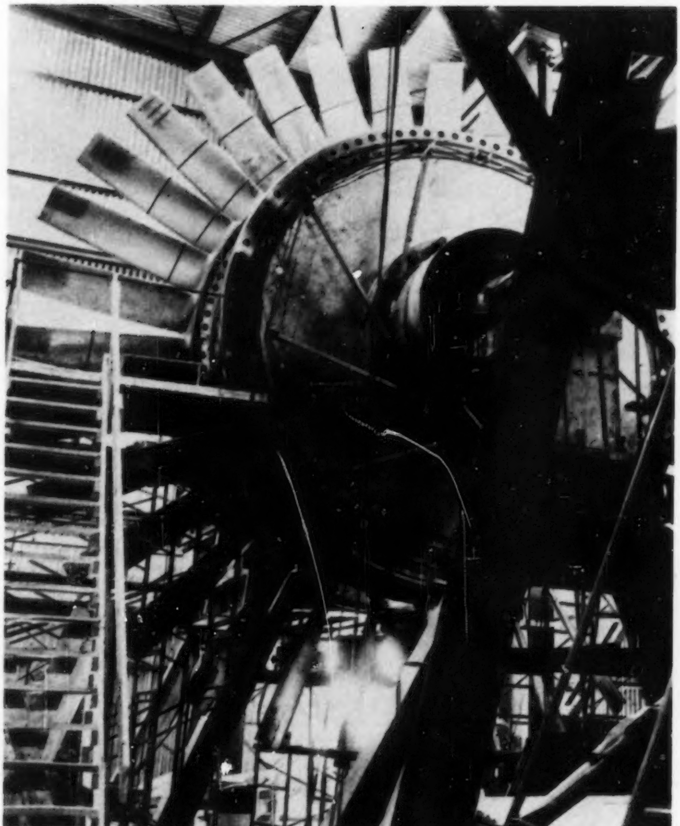


Figure 12
Partially Bladed Disc
Transonic Propulsion Wind Tunnel Compressor

Slide 12 shows one stage of blades assembled on the rotor disc. A special building and jig was set up for the assembly operation. The diameter across the blade tips is 30 feet.

Both of the Propulsion Wind Tunnels have test sections 16 ft. square and 40 ft. long which can be removed from the tunnel circuits and transported to the model installation building, where the work of model installation and instrumentation can be accomplished while other tests are in process in the wind tunnels. It is expected that maximum utilization of the two tunnels will be achieved by this procedure. A discussion of the problems which this and other requirements of unusual nature introduced for the Civil Engineer will be presented by the speaker who follows me.